

Common Cause Case Study - An Estimated Probability of Four Solid Rocket Booster Hold-Down Post Stud Hang-ups

Robert Cross, NASA, Johnson Space Center
2101 NASA Parkway, Houston, TX 77058
email: robert.cross-1@nasa.gov

Abstract – Until Solid Rocket Motor ignition, the Space Shuttle is mated to the Mobile Launch Platform in part via eight (8) Solid Rocket Booster (SRB) hold-down bolts. The bolts are fractured using redundant pyrotechnics, and are designed to drop through a hold-down post on the Mobile Launch Platform before the Space Shuttle begins movement. The Space Shuttle program has experienced numerous failures where a bolt has “hung up.” That is, it did not clear the hold-down post before liftoff, and was “caught” by the SRBs. This places an additional structural load on the vehicle that was not included in the original certification requirements.

The Space Shuttle is currently being certified to withstand the loads induced by up to three (3) of eight (8) SRB hold-down post studs experiencing a “hang-up.” The results of loads analyses performed for four (4) stud hang-ups indicate that the internal vehicle loads exceed current structural certification limits at several locations. To determine the risk to the vehicle from four (4) stud hang-ups, the likelihood of the scenario occurring must first be evaluated. Prior to the analysis discussed in this paper, the likelihood of occurrence had been estimated assuming that the stud hang-ups were completely independent events. That is, it was assumed that no common causes or factors existed between the individual stud hang-up events. A review of the data associated with the hang-up events, showed that a common factor (timing skew) was present. This paper summarizes a revised likelihood evaluation performed for the four (4) stud hang-ups case considering that there are common factors associated with the stud hang-ups. The results show that explicitly (i.e. not using standard common cause methodologies such as beta factor or Multiple Greek Letter modeling) taking into account the common factor of timing skew results in an increase in the estimated likelihood of four (4) stud hang-ups of an order of magnitude over the independent failure case.

I. INTRODUCTION

The Solid Rocket Boosters (SRBs) are mated to the Mobile Launch Platform (MLP) prior to launch with the hold-down post system. Each SRB has four hold-down posts with corresponding support posts on the MLP. Hold-down bolts are inserted through the hold-down post and a nut is used on each end to secure the SRBs to the MLP. The top nuts are frangible, and are ignited at the solid rocket motor ignition command. Each nut has two detonators which are designed to be fired simultaneously. The hold-down bolt then travels downward and is clear of the SRB aft skirt at liftoff.

Should the hold-down bolt not clear the aft skirt before liftoff, the movement of the SRB against the bolt may introduce additional structural loads on the vehicle. This “hang-up” phenomenon may occur on one or multiple hold-down posts, and the resulting additional loads generally increase with the number of stud hang-ups that occur. Through 113 Space Shuttle flights, 25 stud hang-ups have occurred, and two flights have experienced cases where two hold-down posts experienced stud hang-ups. Analyses have been performed to determine if the

additional structural loads imposed by the stud hang-ups are within the certification criteria. Currently, the Space Shuttle is being certified for the case where three stud hang-ups occur. The four stud hang-up case has been informally analyzed for some elements (e.g. SRB, External Tank), and structural loads exceed the design certification, although structural margin may exist such that the actual risk to the crew and vehicle is small [2].

The intent of this analysis is to estimate the probability that four stud hang-ups may occur on a given launch. The results of this analysis show that, for an average flight, the probability of four stud hang-ups is approximately 1 in 4,900, while the maximum expected probability for a flight is approximately 1 in 1,050 [1].

II. BACKGROUND

Stud hang-ups have occurred throughout the flight history of the Space Shuttle, beginning with STS-2. In total, 25 stud hang-ups have occurred on 23 flights. Twenty one flights have experienced a single hang-up while two (2) flights have experienced two (2) concurrent

stud hang-ups. The number of stud hang-ups experienced per mission is shown in Figure 1 for all flights to date.

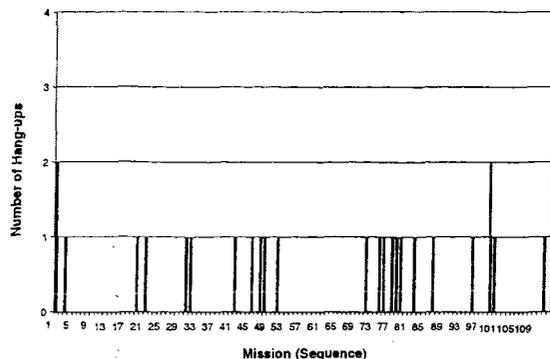


Figure 1: Flight History of Hold-Down Post Stud Hang-ups [2]

The cause of stud hang-ups has been formally investigated by the Space Shuttle Program on three separate occasions. Among the findings of these investigations are:

1. The stud hang-ups are independent of hold-down post position. No one position is more likely than another to experience a stud hang-up.
2. Timing skew, which occurs when the two pyrotechnic charges on a frangible nut do not fire simultaneously, appears to be a necessary or enabling condition for stud hang-ups, but the existence of timing skew does not guarantee that a stud hang-up will occur.
3. There are no specific combinations of stud hang-ups that are worse than others regarding overall structural loads imparted on the vehicle. Different structures of the space shuttle are affected differently by the additional loads imposed by varying combinations of stud hang-ups.
4. Other potential contributors to stud hang-ups are:
 - a) nut orientation, b) stud alignment in bore, c) shoe rotation, and d) combinations of a, b, and c.

As part of the investigations, an analytical motion study [2] was performed to determine the potential impact of the various factors listed above on the downward stud velocity. A minimum velocity was determined to ensure that the bolt cleared the hold-down post before vehicle movement. The results of the study are shown in Figure 2.

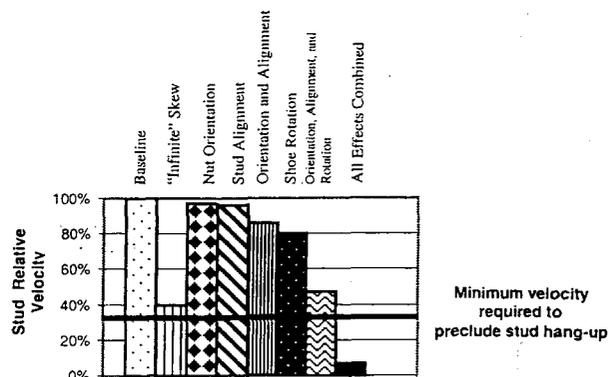


Figure 2, Relative Impact On Average Stud Ejection Velocity [2]

From Figure 2 it can be concluded that stud alignment, nut orientation, and shoe rotation do not result in a stud velocity below the minimum required separately or with all causes combined. The "infinite" timing skew case (where only one side of the pyrotechnics fires) also does not result in a velocity below the minimum required, however, it is very close. It was also found in the motion study that the "infinite" timing skew case may not be the worst case. In other words, there may be some level of timing skew that could result in a velocity below that required. In any case, timing skew is a necessary contributor.

Additional information from the 85th and subsequent flights documenting how often skew was occurring and which hold-down posts were affected was collected. The existence of timing skew was determined indirectly by examination of the frangible nuts or studs. In all cases for which a stud hang-up occurred, timing skew was shown to have occurred at that particular hold-down post.

III. STUD HANG-UPS CONSIDERING TIMING SKEW AS A COMMON FACTOR

As previously discussed, timing skew has been found to be a common factor to all observed stud hang-ups, although it has not been found to be the sole cause of stud hang-ups. The probability of a stud hang-up occurring at a post experiencing timing skew was determined using the flight data from the last 29 flights [3] (STS-85 through STS-113). Six (6) stud hang-ups and 99 timing skews were observed during these missions. The flight data is summarized in Table 2 as the distribution of the number of flights experiencing m timing skews. The probability of a stud hang-up occurring on a hold-down post not experiencing timing skew was assumed to be small

relative to the timing skew case, and therefore neglected (i.e. assumed to be ~0).

Table II: Number of Timing Skews vs. Number of Occurrences

Number of Timing Skews, <i>m</i>	Occurrences in Last 29 Flights (STS-85 through STS113)
0	12
1	1
2	0
3	0
4	4
5	1
6	4
7	3
8	4

A weighted average approach was used to account for the fraction of flights experiencing different numbers of timing skew. First, the probability of up to four stud hang-ups was estimated for each number of timing skews (i.e. $m=0, 1, \dots, 8$). These probabilities were then multiplied by the fraction of flights experiencing each number of timing skews. For each number of stud hang-ups (n), the results for each number of timing skews was summed up to result in a per flight average probability for each number of stud hang-ups. The results are shown in Table 3.

Table III: Estimated Stud hang-up Probability for an Average Launch Assuming Timing Skew as a Common Factor

Number of Stud hang-ups, <i>n</i>	Estimated Mean Probability of Flight Occurrence
0	4 in 5
1	1 in 7
2	1 in 38
3	1 in 348
4	1 in 4913

Considering timing skew as a common factor results in a higher estimated probability of four stud hang-ups occurring than if stud hang-ups are treated as occurring independently (1 in 4,900 compared to 1 in 27,000). The probabilities given Table 3 apply to any "average" launch. That is, these are the probabilities of experiencing stud hang-ups without having any prior knowledge about the degree of timing skew that will be experienced at launch. An uncertainty analysis was performed for the "average" launch probability to estimate the upper (95th percentile) and lower (5th percentile) bounds. The result was an

upper bound of approximately 1 in 690 lift-offs while the lower bound was estimated to be approximately 1 in 64,000 lift-offs.

When timing skew occurs, the probability of occurrence of four stud hang-ups is increased as a function of the number of hold-down posts experiencing the skew. The worst case probability of a four stud hang-up occurrence is approximately 1 in 1050 when all eight hold-down posts experience timing skew. Based on this analysis and assuming 30 flights remain in the Shuttle Program, four of those flights can be expected to experience timing skew on all eight hold-down posts and thus be exposed to this maximum probability. Currently no means exist to measure expected timing skew prior to a launch and the flights most at risk of experiencing four stud hang-ups cannot be identified.

The key results from the analysis are summarized in Table 4.

Table IV: Key Results for the Probability of 4 Stud hang-ups Considering Timing skew as a Common Factor

Parameter Description	Estimated Mean Probability of Flight Occurrence
Estimated Mean Probability of 4 Stud hang-ups for a Single "Average" Flight	1 in 4913
Estimated Maximum Probability of 4 Stud hang-ups for a Single Flight Experiencing Timing Skew (8 hold-down posts affected)	1 in 1050
Estimated probability of at least one occurrence of a 4-Stud hang-up for the Remainder of the Shuttle Program (Assumed 30 Flights) Based on "Average" Flight Risk for a Single Flight	1 in 164

IV. CONCLUSIONS

Several conclusions may be drawn from this analysis with regard to the likelihood of four stud hang-ups.

1. The likelihood of multiple hang-ups is significantly higher than previously thought (assuming independent events) due to the common factor of timing skew.

2. The likelihood of multiple hang-ups occurring for each flight varies based on the number of timing skews occurring.
3. Based on sensitivity studies, the likelihood of five hang-ups is significantly less than four, assuming no common cause beyond timing skew.

It is important to note that this analysis only evaluated the likelihood of stud hang-ups occurring and not the risk to the crew or vehicle. Although informal structural analyses show the violation of certification limits for the four hang-up case, they also show there may be significant structural margin to the ultimate load, in which case the actual risk would be small.

REFERENCES

1. R. CROSS, "SSMA-05-004, Analysis to Estimate The probability of 4 of 8 Solid Rocket Booster Hold-Down Post Stud Hang-ups," Johnson Space Center, Houston, Texas, National Aeronautics and Space Administration, February 17, 2005
2. C. E. LARSEN, B. WALLS, and D. PAUL, "SRB Holddown post Stud Hang-up Loads," Johnson Space Center, Houston, Texas, National Aeronautics and Space Administration, February 6, 2004
3. Post-Flight data, United Space Alliance, SRB Element.